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Development of a numerical test bed for ultrasonic inspection of highly reinforced concrete

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Abstract

Reliable non-destructive evaluation of heavily reinforced large concrete structures becomes more important every day as the US civil infrastructure continues to age. Use of low frequency ultrasound has shown some success, however, as the level of reinforcement and thickness increase, inspection issues remain. There is a need for tools to design, optimize and evaluate inspections to estimate detection capability as a function a wall thickness and level of reinforcement. A numerical testbed is being developed to meet this need. Using a 2D approximation simulation of inspection of concrete up to 1m thick and using frequencies of 50kHz can be assessed efficiently. Image processing techniques were used to mesh images of concrete microstructure and to generate a realistic local geometry for concrete samples. For initial code validation, the scattering response from a 3mm side drilled hole (SDH) in immersion was assessed. The code had good agreement with both analytical and experimental results. The code is being extended to consider various rebar geometries and aggregate combinations and initial data are reported. Material properties used were based on experimental measurements. The test bed is now being used to consider a sparse phased array, to optimize sensor placements, and evaluate inspection performance.

Keywords

Ultrasound, Image processing, Ultrasonics, Antennas

Disciplines

Acoustics, Dynamics, and Controls | Structural Materials | Structures and Materials

Comments

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Reliable non-destructive evaluation of heavily reinforced large concrete structures becomes more important every day as the US civil infrastructure continues to age. Use of low frequency ultrasound has shown some success, however, as the level of reinforcement and thickness increase, inspection issues remain. There is a need for tools to design, optimize and evaluate inspections to estimate detection capability as a function a wall thickness and level of reinforcement. A numerical testbed is being developed to meet this need. Using a 2D approximation simulation of inspection of concrete up to 1m thick and using frequencies of 50kHz can be assessed efficiently. Image processing techniques were used to mesh images of concrete microstructure and to generate a realistic local geometry for concrete samples. For initial code validation, the scattering response from a 3mm side drilled hole (SDH) in immersion was assessed. The code had good agreement with both analytical and experimental results. The code is being extended to consider various rebar geometries and aggregate combinations and initial data are reported. Material properties used were based on experimental measurements. The test bed is now being used to consider a sparse phased array, to optimize sensor placements, and evaluate inspection performance.

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1. INTRODUCTION

The United States civil infrastructure is extensive and varied. It ranges from bridges to nuclear power plants, each type of which presents unique challenges when assessing them nondestructively. Of these challenges, one of the most difficult is to ultrasonically examine the containment for a nuclear power plant from one side only. A joint federal and industry assessment identified the concrete structures and containment degradation as one of the most significant technical issues that must be addressed for nuclear power plants to safely operate beyond 60 years [1]. Therefore methods must be developed to address the challenges with nondestructive evaluation degradation to ensure that these systems can perform their intended functions. An example of such a structure is shown in Fig 1. The source of the complications in inspection are derived from the scale and heterogeneity of the materials which comprise the system to be inspected. A containment is typically about 1m thick concrete, highly reinforced and steel lined, with the aggregate in the concrete locally sourced.

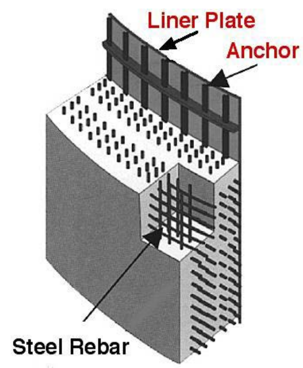

Figure 1. Containment Cross Section schematic (tendons not depicted) [2]

Defects found in containment structure can be fabrication flaws, such as voids, delamination, cracking, honeycombing, and foreign materials, all of which can lead to a reduction in strength of the concrete and potentially degrade the rebar and the containment liner [3]. These defects typically have to be quite large, typically of the order of square meters, before being considered to significantly degrade margins of safety

Concrete can be inspected using a range of NDE modalities [4], but such inspection can be challenging. In the case of containment structures it is the thickness and high level of reinforcement which limit what can be achieved using commercially available equipment. Recent success in imaging thick concrete with the application of arrays and a Large Aperture Ultrasonic System (LAUS) [5, 6] has demonstrated potential for the detection and characterization of defects within such concrete. With these successes, there is interest in moving the concepts forward to a sparse array and in providing modeling tools to design, evaluate and optimize inspections and then to estimate detection capability as a function of wall thickness, placement and level of reinforcement

2. METHODOLOGY

A numerical testbed is being developed to meet this need. Many simulations can be run to systematically evaluate different configurations and parameters within the inspection, and determine the impact on potential defect detectability. To run the multitude of simulations a computationally efficient schema will have to be employed. Techniques such as Finite Difference Time Domain and Elastodynamic Finite Integration Technique (EFIT) have performed well with limited computational overhead. Recent work by, S. Beniwal et al. [7], using Finite Difference Time Domain has shown success in identifying damage near rebar using numerical models and visualizations. For this work an

EFIT approach was adopted and employing flexible boundary conditions and the code was optimized to use GPU processing [8]. EFIT uses a velocity-stress formalization and applies the integral form of the equations of motion shown in Eq. 1:

$$\begin{aligned}\iint_{Axy} \dot{v}_x dxdy &= \iint_{Axy} \left[\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y} + f_x\right] dxdy \\ &= \oint_{Axy} [\sigma_{xx} dx - \sigma_{xy} dy] + \iint_{Axy} f_x dxdy\end{aligned} \tag{1}$$

The integrals can be evaluated by multiplying the mean value of the integrand by the corresponding area of the integration cell (Eq. 2):

$$\rho \dot{v}_{x,\, i,\, j}\, \Delta x \Delta y = \left[\sigma_{xx,\, i+1,j} - \sigma_{xx,\, i,j}\right] \Delta y + \left[\sigma_{xx,\, i,j} - \sigma_{xx,\, i,j-1}\right] \Delta x + f_{x,i,j} \Delta x \Delta y \tag{2}$$

This method necessitates the use of staggered grids where velocity and stress are updated in a pattern so that time and space discretization are the same. Using a 2D approximation grid sizes are modest and manageable and concrete up to 1m thick can be considered using inspection frequencies of 50 kHz. In setting up the model, image processing techniques were used to define the mesh, in particular images of the typical paste-aggregate systems in concrete were used to generate realistic heterogeneity. To guarantee numerical stability spatial increments are 10 per wavelength $\Delta x \leq \frac{V_{min}}{10F_{max}}$ where V_{min} is the lowest velocity phase velocity in spatial domain. The highest frequency F_{max} in the spectrum then limits the time step which must be $\Delta t \leq \frac{\frac{1}{\sqrt{2}}\Delta x}{V_{max}}$ where V_{max} is the maximum phase velocity in spatial domain [9]

3. RESULTS AND DISCUSSION

To validate the model a comparison of the simulation results, photoelastic visualizations, and an analytical test case was performed. A longitudinal wave from a 2.25MHz 25x12mm transducer impinging a 5mm side-drilled-hole (SDH) in sodaglass was simulated and compared to photoelastic visualizations. There is good agreement with the numeric visualizations and the photoelastic results as shown in Fig. 2.

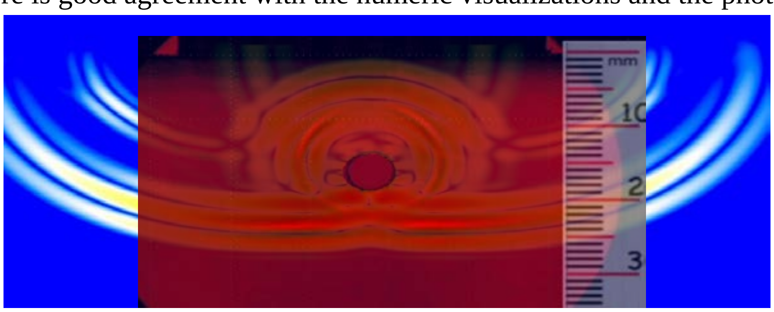

Figure 2. Wavefield comparison for numerical and Photoelastic Visualization– 2.25 MHz rectangular transducer

A simulation of the waves scattered by a 3mm (1.07 D/λ) SDH in 7075 aluminum was used to validate the separation of variables solution to the problem. An immersion setup with 16mm of water path and a 2.25MHz with a 0.25 diameter transducer were used to send a longitudinal wave to the SDH. The SDH center was 30mm from the surface of the aluminum block. The time domain signals are shown in Fig. 3 and the corresponding scattering coefficient data are given in Fig 4.

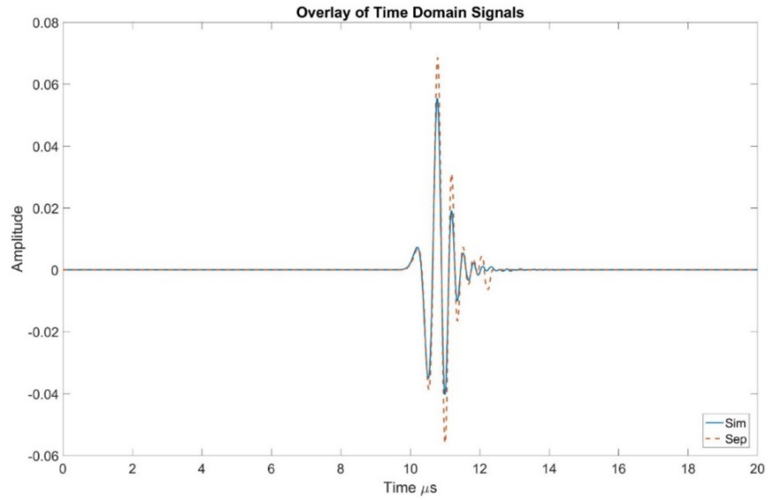

Figure 3. Time Domain Response from Simulation and Separation of Variables Solutions

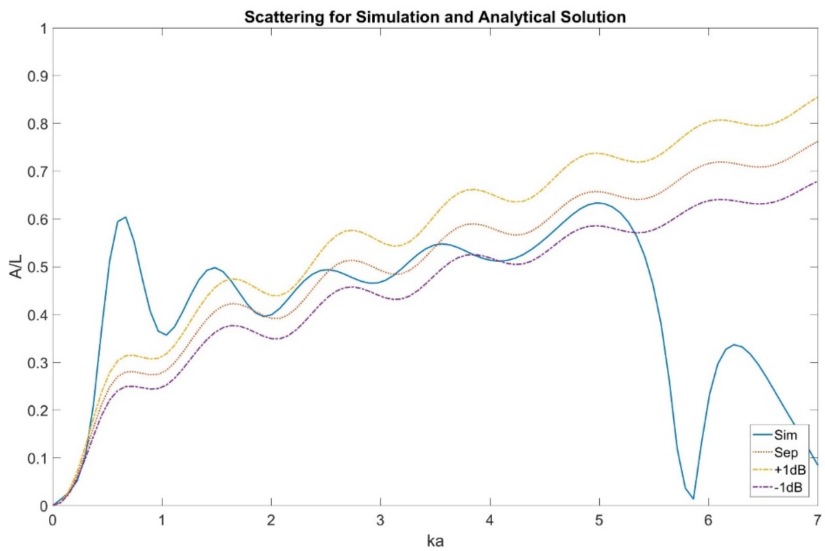

Figure 4. Scattering Response from Simulation and Separation of Variables Solution

There is good agreement in the time domain (Fig 3) and within the bandwidth of the applied signal, there is agreement within 1dB of the analytical solution as seen in Fig 4. With this initial validation complete simulations of concrete were developed and assessed. Concrete microstructure was modeled using a free (open source) program from NIST called Virtual Cement and Concrete Testing Laboratory. The aggregate distributions were then imported and data in images were processed using image processing software to give arrays where material parameters could be applied.

Examples of visualizations for waves from a single ribbon transducer giving 2-D waves into samples have been modeled. The visualizations have been created but they have not yet been experientially verified. An example of such data is shown in Fig 5. Arrays of receivers detect displacements at the surface as “RF” or seismometer point data for analysis.

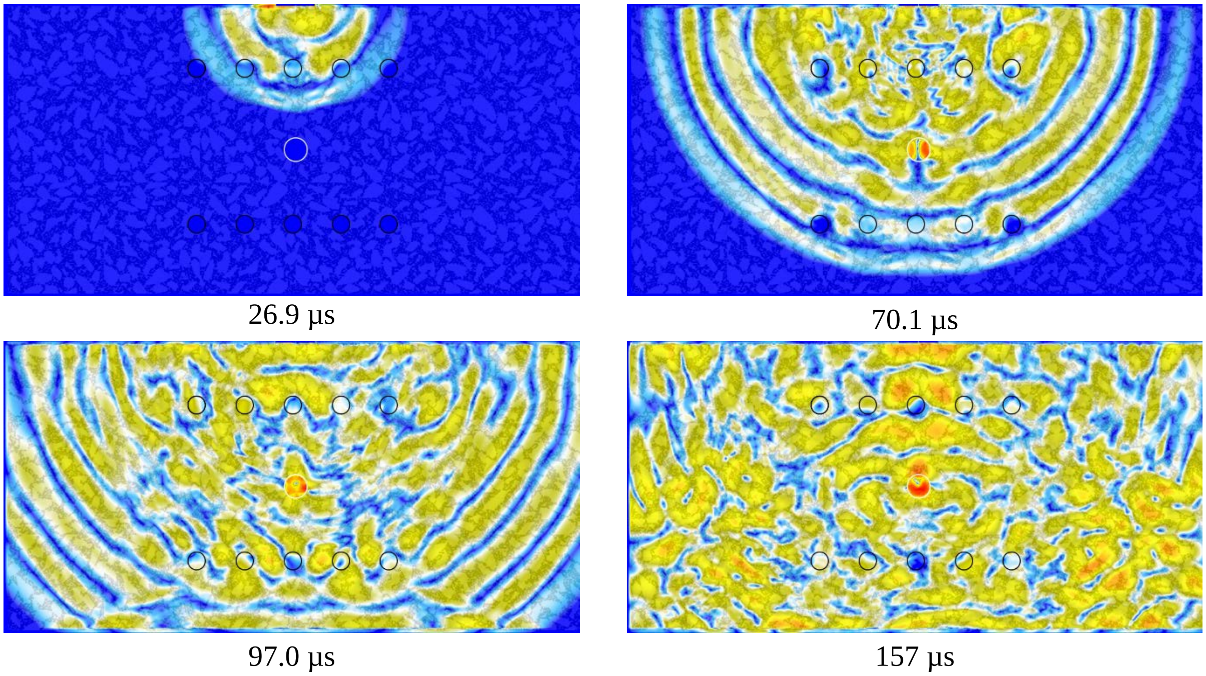

Figure 5. Example of numerical visualization "snapshots" into sample with two layers rebar and center void

4. CONCLUSION AND FUTURE WORK

A numerical testbed has been developed to optimize and evaluate the detection capabilities of single sided access inspections using sparse arrays of highly heterogeneous structures. The model demonstrated that it performs well for a few test cases. Work to date shows that simulations involving concrete, rebar, and void defects can be efficiently processed by the model and the model's response will be validated in future work.

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